xiv. Helical Dipoles

Helical magnets control the spin of the polarized protons in RHIC. The basic construction unit is a superconducting magnet producing a 4 T dipole field that rotates through 360 degrees in a length of 2.4 m [WI97, WI99a]. These magnets are assembled in groups of four to build four Snakes that control spin in the lattice and eight Rotators that orient spin axially at two collision points. Thus, the complete program requires 48 magnets.

A cross section drawing of the helical magnet is shown in Fig. 14-1. Parameters for the magnets are given in Table 14-1. Because multiple current leads exit each cryostat, a low current design (320A) was used to minimize the cryogenic load due to the leads. By the standards of superconducting magnets, the field quality requirements are relatively modest (harmonics < 10^{-3} of the main field). The error allowed on the rotation angle is 2°.

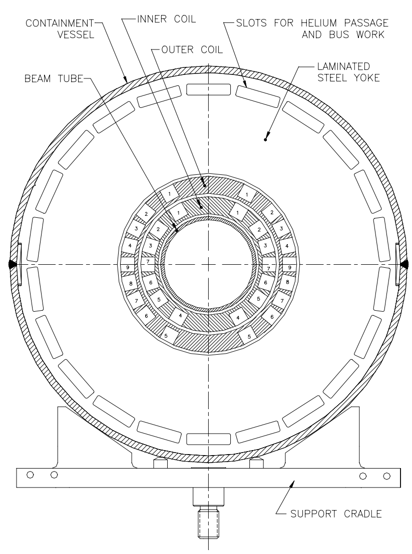

Fig. 14-1. Cross section of the helical dipole magnet. The yoke OD is 356 mm. The innermost conductor is at an ID of 100 mm.

Table 14-1 Selected parameters of the RHIC helical dipole magnets.

Parameter	Units	Value
Aperture	mm	100
Magnetic length	m	2.4
Field	T	4
Current	A	320
Number of turns		1680
Inductance	H	4.8
Stored energy @ 4 T	kJ	240
Diameter of yoke	mm	355.6
Num. of strands in cable		7
Strand diameter	mm	0.33
Cu to non-Cu ratio		2.5:1

The coil structure consists of two aluminum tubes, each with slots as shown in Fig. 14-2. These are filled with Kapton-insulated superconducting cable. The tubes are surrounded by a yoke made of single piece, low-carbon steel laminations. Holes near the outer perimeter of the yoke allow for tie rods, warm-up heaters, passage of helium coolant, and bus work for magnet interconnections. The slots rotate along the length of the magnet but the holes in the yoke do not, so the yoke laminations were designed with rotational symmetry in mind. Azimuthal Lorentz forces are contained in the individual slots. The outward Lorentz forces are ultimately contained by the single piece yoke. In the ends, the difficult Lorentz force problem is again solved by containing the forces in the individual slots.

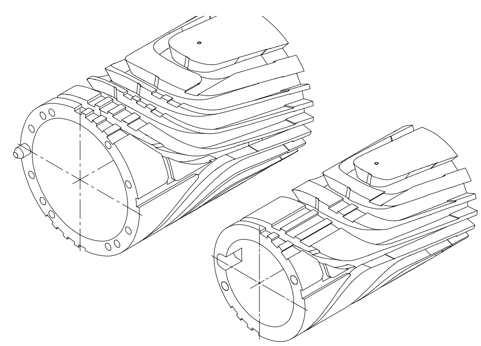

Fig. 14-2. Drawing of the coil tube ends. End Lorentz forces are contained in the slots.

The superconducting cable is placed by hand and without tension into the slots in an ordered array. The width in the slots is such that 12 turns of the round cable, which is about 1.1 mm in diameter, have an average of 25 μm space between turns. A layer of B-stage fiberglass/epoxy with adhesive film on each side is placed between each layer. After winding, press plates of 3.1 mm thick G10 are applied to each slot. A Kevlar wrap is then applied to the tube under tension. In the subsequent curing operation, the stretch in the Kevlar allows the press plates to move radially inward without losing all tension, thereby compressing the windings and removing voids in the slots as the epoxy softens and fills the remaining spaces. Helium is still able to penetrate this package and fill the ~ 10% free space inside the Kapton wrap and around the wires of the cable. At the ends of the magnet, space is left in the slots to accommodate the axial growth of the coil during curing. Voids remaining in the ends after curing are filled with epoxy by hand. After curing, the Kevlar is removed so that the leads can be secured. The coil is then wrapped with fiberglass cloth, Kevlar under tension, and Tedlar. (The Tedlar prevents epoxy in the next layer from seeping into the Kevlar). Multiple layers of fiberglass cloth and epoxy are applied to build the radial thickness needed for the final step, machining the cylinder to a precise radius (~ 50 μm). The epoxy cures at room temperature.

The two coils are assembled, aligned, pinned together, and bolted to a plate that serves as the primary alignment reference of the magnet. The laminations are weighed before assembly to the coils. The length of the yoke is set by tie bars. The tie bars and coils are held on a plate at only the lead end of the coils. Thus, the coils can follow the contraction of the aluminum tube during cooldown. Fig. 14-3 shows a section cut from a prototype helical magnet [OK00].

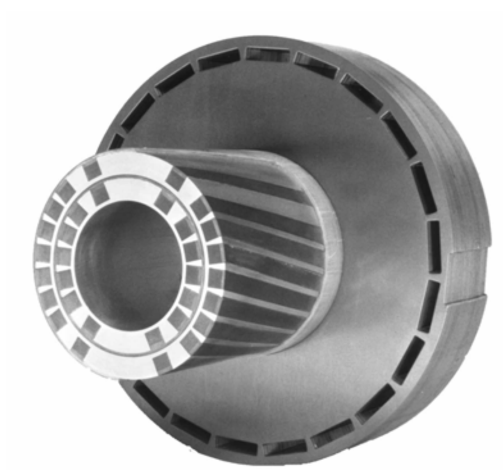

Fig. 14-3. Photograph of a section cut from a prototype helical magnet.

Each of the individual windings is connected in a series connection on a circuit board at the end of the magnet. A 50 mΩ resistor is connected across each of the windings to avoid overheating during a quench. The large inductance of the windings (0.3 H on average) and the 50 mΩ parallel resistance lead to an indeterminate field in the magnet when it is ramped. This is acceptable because the magnet is designed to be operated only in a DC mode or with very slow (< 1 A/sec) ramp rates.

The magnets were tested individually in a vertical dewar filled with liquid helium. Quench test results from the magnets that were installed into the first Snake are shown in Fig. 14-4. Initially, magnets were trained to currents close to conductor limit, ~ 410 A. The training was monotonic but sometimes slow at the highest currents. The test protocol later called for training the magnets to 360 A, about 10% above the maximum operating current. Magnets have typically reached 360 A in a few quenches. See [WI03] for test results from all 48 magnets.

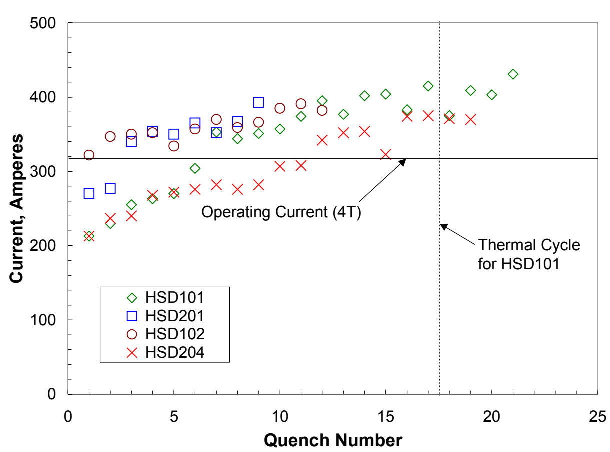

Fig. 14-4. Quench performance of the four magnets of the first Snake. After some initial training, each reached a current comfortably above the maximum operating point of 4 T. A thermal cycle showed no retraining.

Ideally, the integral field of each helical magnet will be zero. The acceptance criterion calls for it to be small: $\left[\left(\int B_y(z)\,dz\right)^2 + \left(\int B_x(z)\,dz\right)^2\right]^{1/2} < 5\times10^{-2}\ \mathrm{T\cdot m}$. In terms of the rotation angle of the spin vector, this tolerance is ~ 1.9 degrees. The integral field is measured using a 3.57 m long, 48 mm diameter rotating coil. All magnets tested thus far have easily met this requirement.

Helical magnets have axial fields in the magnet straight section. They can be expressed in cylindrical coordinates using Bessel functions as basis functions [FI97,WI99b]. In these magnets the resulting harmonic coefficients are close to those for straight magnets; the harmonics measured with the short (51 mm) standard harmonic coil used require a correction of only a few percent. This coil has diameter 68 mm. Field quality measurements at the center of a typical magnet as a function of current are shown in Figs. 14-5 through 14-7. The decrease in the transfer function and the increase in the sextupole with current are caused by saturation of the steel yoke, which is undersized in order to limit the physical size of the magnet. Field quality measurements made by stepping the coil through the length of the same magnet at three fixed currents are shown in Figs. 14-8 through 14-11.

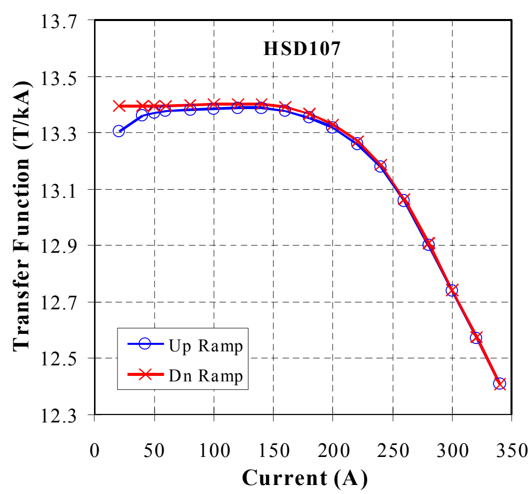

Fig. 14-5. Transfer function at the center of HSD107

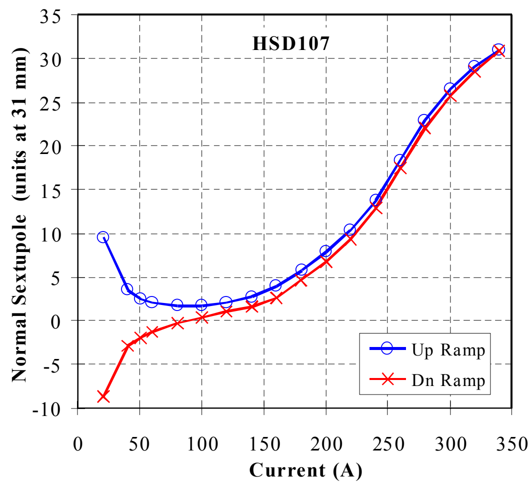

Fig. 14-6. Normal sextupole harmonic at the center of HSD107.

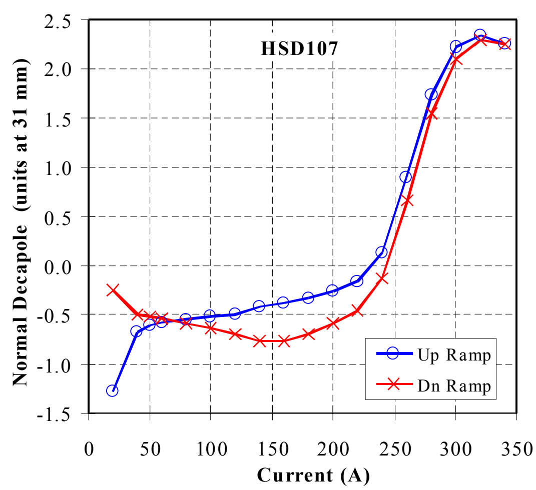

Fig. 14-7. Normal decapole harmonic at the center of HSD107.

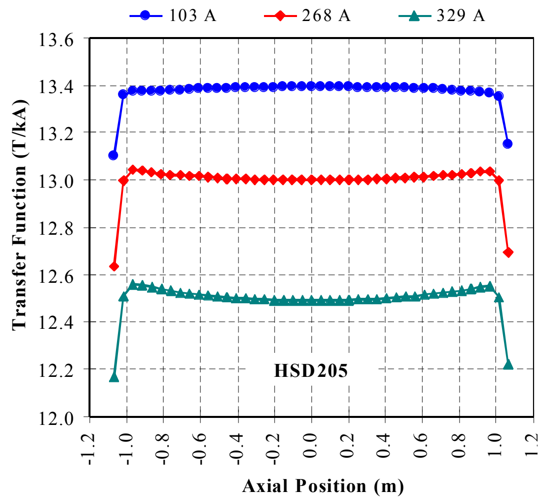

Fig. 14-8. Axial scan of the transfer function in HSD107.

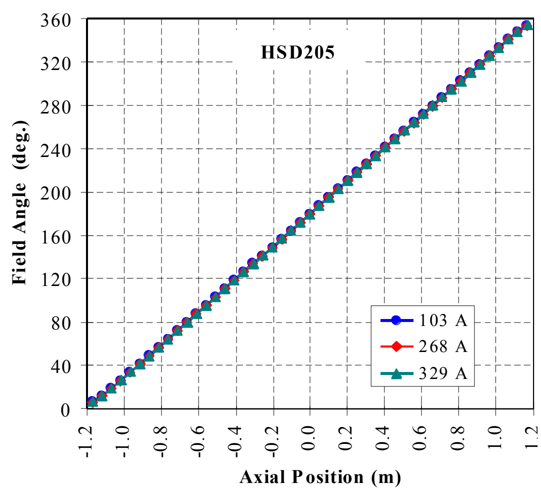

Fig. 14-9. Field angle as a function of the axial position in HSD205.

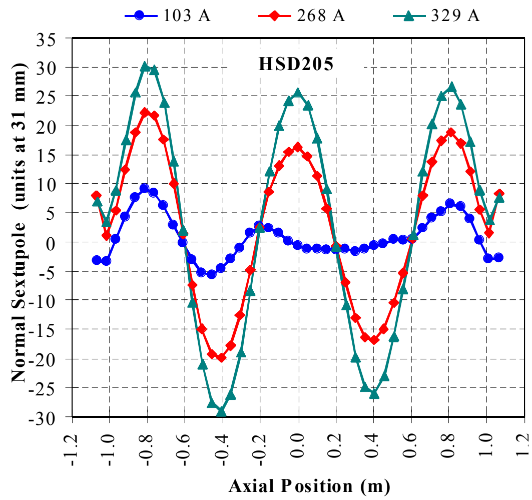

Fig. 14-10. Normal sextupole harmonic as a function of the axial position in HSD205.

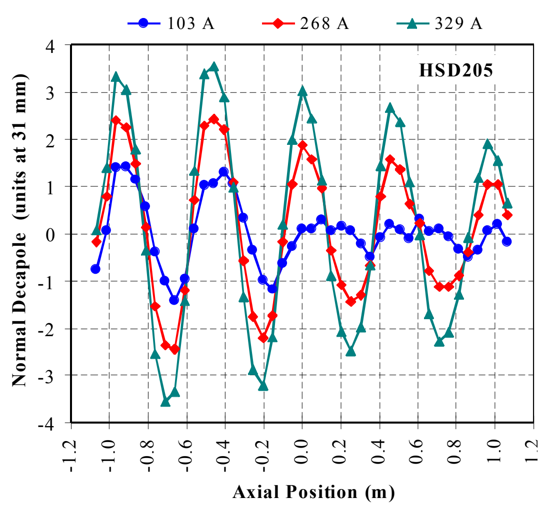

Fig. 14-11. Normal decapole harmonic as a function of the axial position in HSD205.